Variability of the Galactic CRs and Diffuse Gamma-Ray Emission Predicted with GALPROP

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Diffuse Emission at TeV Energies

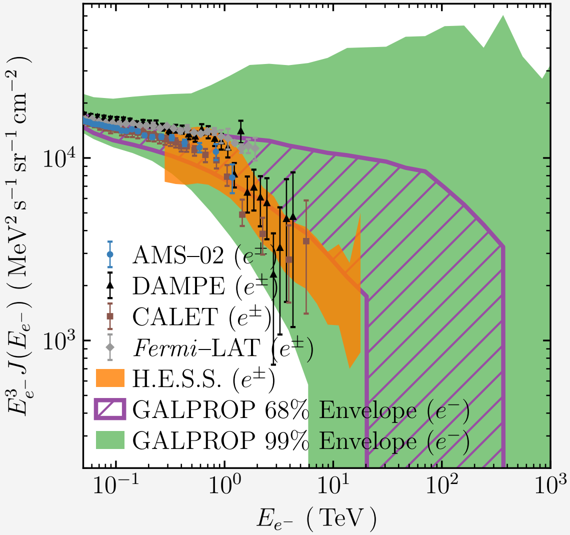
- Steady-state CR diffusion models have been standard for the 100 MeV to 100 GeV regime for decades.
- Observations of the diffuse emission are now being performed at higher energies. We need to connect the diffuse emission across the GeV–PeV regimes.
- Previous work characterised the modelling uncertainty in the TeV regime over a grid of steady-state models.
- For higher energies the rapid energy losses of the electrons necessitate the consideration of discrete CR injection sites.
- The TeV γ–ray emission is then expected to vary on timescales $\sim$ lifetimes of the sources.
- How large are these variations? Can a component of discrete sources explain the TeV–PeV γ–ray excess observed by LHAASO and other observatories?

Model Setup

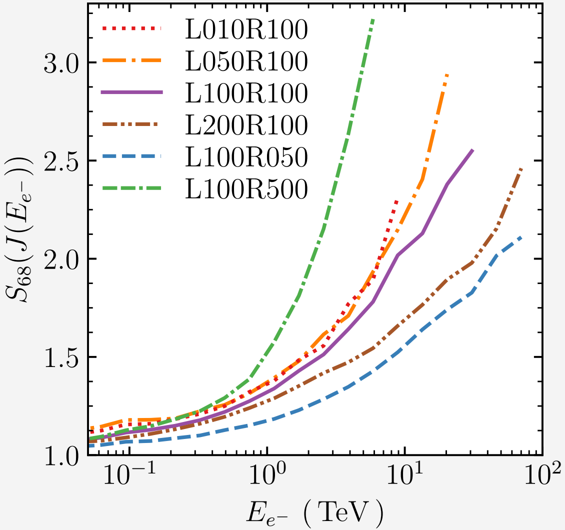
- CR hadrons are injected via a steady-state, smoothly varying distribution. CR leptons are injected via discrete sources with finite lifetimes.
- Source lifetimes are varied from 10–200 kyr.
- Creation rates are varied from 0.02–0.002 yr^{-1} (average interval between sources of 50–500 yr).
- We analyse 5 Myr of simulation results for six different combinations of source parameters (L010R100, L050R100, L100R100, L200R100, L100R050, L100R500).
- Injection spectra are fit such that their post-diffusion spectra at the Solar position reproduce measurements on the final timestep.
- ISM gas from Jóhannesson et al. 2018, SA50 source distribution, R12 ISRF, PBSS GMF (see Porter et al. 2017, and references therein).

CR Electron Variability Throughout the Milky Way

- Local measurements show a potential cutoff around 1 TeV.
- Cutoff is reproduced for times with no nearby sources.
- $\Rightarrow$ Altering the Galaxy-wide injection spectrum is *not* required to reproduce the cutoff.
- This variability will be imparted onto the γ rays, and can be quantified to define a modelling uncertainty.



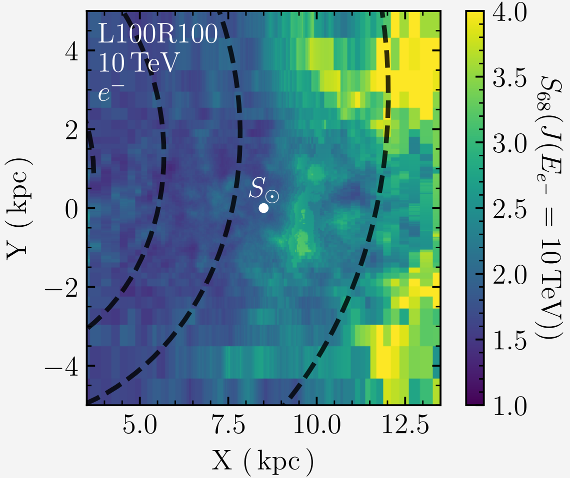
Measuring the Variability



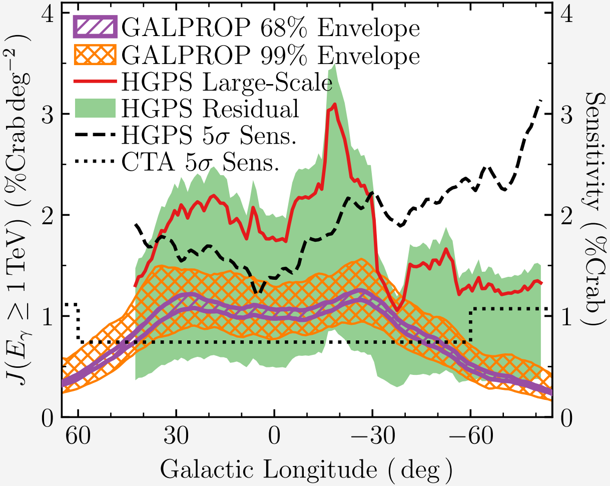
- Need to define a measurement of the variability.
- However, fluctuations are non-symmetric and weighted towards large increases.
- Define a 'containment factor', which is the factor difference from the steady-state values that contains some percentage of the data.
- For example, 68% of the time-dependent values are within a factor S_{68} from the steady-state flux.

CR Electron Variability Throughout the Milky Way

- Can apply the containment factor analysis throughout the Milky Way.
- Below ∼1 TeV the electron flux is steady throughout the Galaxy.
- Above 10 TeV the electron flux is steady within the spiral arms and fluctuates by factors ≳2 for the inter-arm regions.
- The outer-Galaxy fluxes vary by factors ≳4.

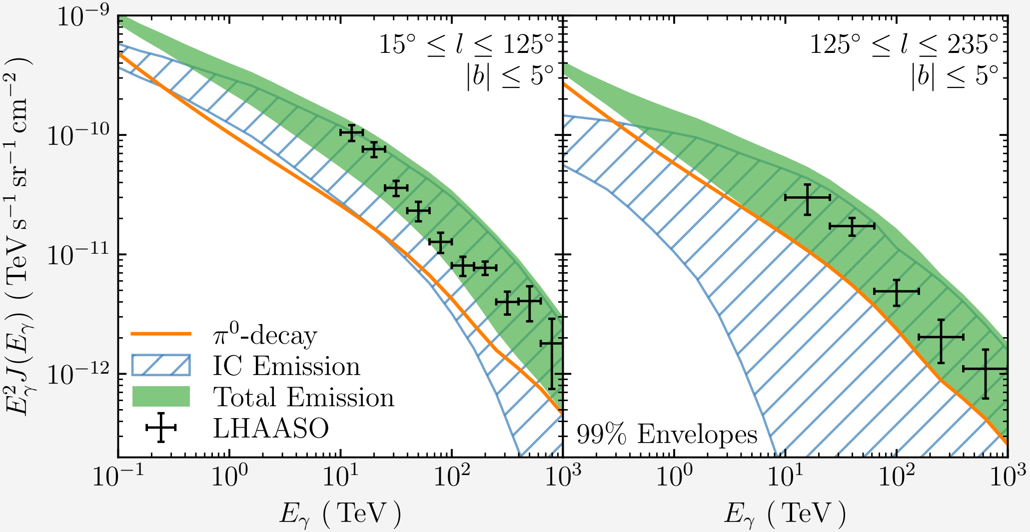


Comparing GALPROP to H.E.S.S.

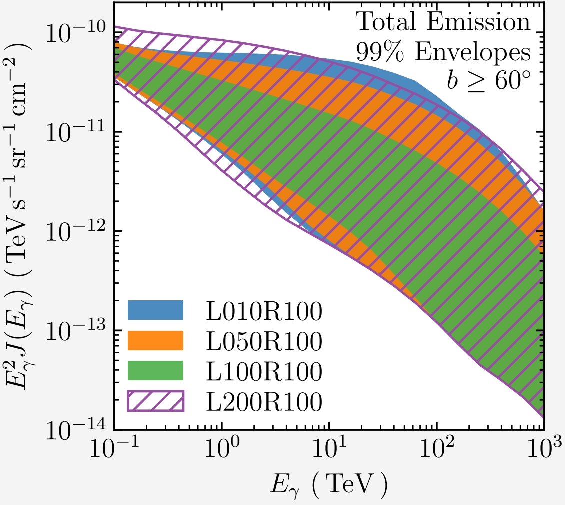


- HGPS large-scale ⇒ flux above 1 TeV minus resolved sources.
- HGPS residual ⇒ large-scale minus unresolved sources (includes flux uncertainty).
- 5σ sensitivities for HGPS and CTA's proposed 10-year plan.
- GALPROP agrees with the lower limits of the HGPS observations.
- CTA can be expected to make a 5σ detection with current plans.

Comparing GALPROP to LHAASO



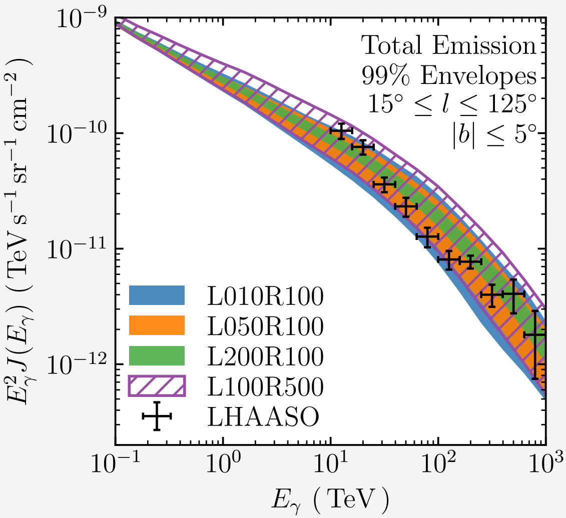
Polar Region Flux



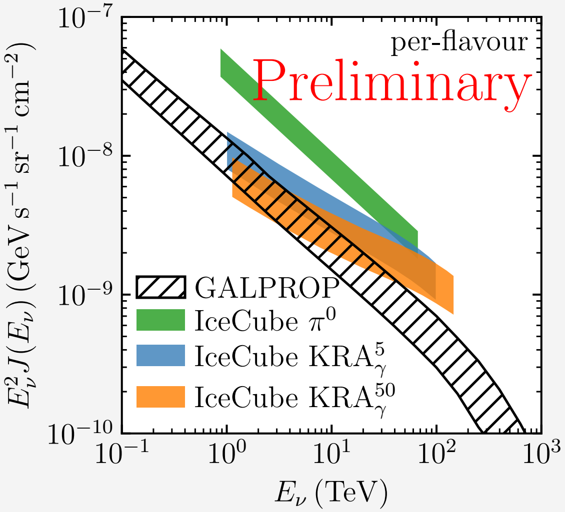
- Polar region flux above 1 TeV is Galactic in origin.
- For most timesteps the IC emission is the dominant component for both Galactic polar regions.
- The polar flux then provides an opportunity to constrain the electron flux away from the Solar neighbourhood with future observations.

Constraining the Source Parameters

- Lxxx ⇒ source lifetime in kiloyears.
- Ryyy ⇒ average time between source creation in years.
- Showing four source parameter combinations to represent the variability across the time-dependent models.
- Current measurements of the diffuse emission are unable to further constrain these source parameters.



Comparing GALPROP to IceCube



- IceCube recently announced model-dependent observations of Galactic neutrinos.
- This neutrino emission can be used to constrain hadronic components.
- All neutrino fluxes are per-flavour.
- GALPROP predictions are in agreement with the model-dependent IceCube fluxes.
- Working on quantifying the spatial coincidence between GALPROP and IceCube.

Summary

- The leptonic CR and γ–ray fluxes above 1 TeV experience large fluctuations due to the discrete nature of the CR accelerators.
- Accurate γ–ray predictions will require precise locations of all CR accelerators in the Galaxy. As precise locations are not currently known, we have found the variability of the models.
- We found CTA should be able to observe the diffuse emission for the central 90° of the Galactic plane.
- For γ rays in the TeV–PeV regime an unresolved leptonic component is able to reproduce the LHAASO excess with no alterations to the model.
- While the CR source parameters (lifetimes and creation rates) impact the diffuse emission, we are unable to recover their values from current measurements of the diffuse emission.

See arXiv:2411.03553 for more information.

Additional Slide: PWNe as Leptonic PeVatrons

- LHAASO Collaboration, et al. 2021 found >1 PeV γ rays from the Crab Nebula. This result would require >1 PeV electrons.
- Cao, Z., et al. 2021 analysed 12 γ–ray sources with LHAASO, finding γ rays up to 1.4 PeV. The only confirmed PWNe was the Crab Nebula, and an additional nine sources have potential PWN counterparts.
- Burgess, D., et al. 2022 found 2 PeV electrons are required to explain the γ–ray emission around the Eel PWN.
- Liu, Y.-M., et al. 2024 looked at 17 PWNe, 16 of which show CR electrons >100 TeV. They state that 3 PWNe have CR electrons confidently confirmed $>$PeV. Additionally, leptonic injection is approximately constant for the first 15 kyr.
- +others

Additional Slide: Bibliography

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